HiX2000: Theory Summary

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We summarize the theoretical consensus of the HiX workshop concerning those measurements which seem most appropriate for inclusion in the "white paper" being prepared to justify the proposed 12 GeV upgrade at Jefferson Lab. The criteria for inclusion are that such measurements should be decisive, not possible elsewhere and should answer crucial physics questions with broad implications.

I. INTRODUCTION

Although a great many innovative and exciting suggestions were made for physics investigations following the proposed 12 GeV upgrade, it was eventually necessary to focus on two main themes. We deal with these in turn below. The first is the possibility of unambiguously determining the valence u and d quark distributions of the free nucleon in the region of Bjorken x above 0.4 (and as close as possible to 1). In particular, while the valence u distribution is relatively well known, it has recently been realized that the d distribution is very poorly determined in this region – at least if one requires that the determination should be demonstrably model independent. For the polarized valence distributions, Δu and Δd, the situation is even worse, with no measurements at all for x above 0.5.

Experiments with ^{3}He and ^{3}H targets, following the 12 GeV upgrade, could resolve the longstanding problem concerning the valence d distribution for x up to 0.85 – establishing finally whether or not the predictions of perturbative QCD are correct. As a by-product one would complete our knowledge of the EMC effect over the full range of nuclear mass number. Using polarized proton and ^{3}He targets one could also complete the determination of the polarized distributions Δu and Δd over the same region of x. The result of this program would be a definitive picture of the valence structure of the nucleon, including its spin dependence.

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Measurements using polarized proton and ^{3}He targets at the 12 GeV facility would also allow one to definitively establish the twist-3 component of the structure functions g_{2p} and g_{2n} – at least for low moments. This major advance would be made possible by a factor of 10 improvement in statistics over what has hitherto been possible and over a much greater range of Bjorken x: $0.3 \leq x \leq 0.8$. From the theoretical point of view the twist-3 structure function provides totally novel information on the internal structure of the nucleon – information that should be accessible to lattice QCD within the same ten year time frame.

At a later and more mature stage of development of the facility other exciting possibilities arise. One could use the knowledge of $u, d, \Delta u$ and Δd, at relatively large x, to test the validity of duality in this region and if it works to use it to obtain insight into these distributions for x as large as 0.95. We could also use this knowledge to test the utility of semi-inclusive measurements for determining spin and flavor dependence of parton distributions. If these tests are successful one could apply these methods to an accurate determination of the spin and flavor dependence of the nucleon sea in the region $x > 0.2$. Finally, one could use a tensor polarized deuteron target to probe completely new structure functions such as b_1 for x near and beyond 1.

II. LARGE-X VALENCE DISTRIBUTIONS

The distribution of the valence quarks in the nucleon is one of its most fundamental properties. Because of the relative 4:1 weighting for electromagnetic probes, the proton structure function primarily constrains the u distribution in the proton. To determine the d distribution requires a second measurement, traditionally using the deuteron. While the approximate treatment of the deuteron as a neutron and a proton at rest, so that $F_2^n \approx 2F_2^d - F_2^p$, is not too bad for x below (say) 0.4, it breaks down badly at large x. Nevertheless it is only in the past few years that it has been realized that a realistic treatment of the effects of fermi motion and binding in the deuteron lead to an extracted neutron structure function which is quite different from that used in all standard parametrizations of parton distributions. In particular, a reanalysis of SLAC data by Melnitchouk and Thomas [1] suggested that the d/u ratio may actually approach the pQCD prediction of 1/5 [2], rather than 0 as $x \to 1$.

While this analysis is persuasive [3], our knowledge of such fundamental properties should not be model dependent. Fig. 1 shows the present, appalling state of our knowledge of d/u at large x. It is clearly vital to find a facility and a technique that allow us to map out the valence distributions

[bb = 35 140 540 710, scale = 0.5]lqpap$_d ou.ps$
FIG. 1. Ratio of $(d+\bar{d})/(u+\bar{u})$ at $Q^2 = 10$ GeV^2, showing the present uncertainty in the region $x > 0.4$ – from Ref. [4].

in a model independent manner over the complete x range and this problem was addressed by a number of participants at the workshop including Bosted, Forest, Klein, Leader, Melnitchouk, Meziani, Olness, Petratos and Scopetta. It is in this context that the idea of using ^{3}He and ^{3}H targets is extremely exciting. The fundamental point is that charge symmetry is a very good symmetry for strongly interacting systems and these two mirror nuclei are related by charge symmetry. In the limit of exact charge symmetry the distribution of protons (the neutron) in ^{3}He would be the same as that of neutrons (the proton) in ^{3}H – regardless of the size of the EMC effect in these nuclei! A measurement of the structure functions of these two nuclei would then allow us to determine F_2^n/F_2^p exactly.

In practice there are electromagnetic corrections to be made and charge symmetry is slightly broken by the strong interaction. Nevertheless, exact Faddeev calculations of the structure of the A=3 nuclei allow us to estimate these corrections quite accurately – and to test the dependence of the nuclear structure functions on the two-nucleon potential used. In order to understand the analysis to be applied to the data we need to define the ratios:

$$(R^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n} \quad ; \quad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}, \tag{1}$$

and the super-ratio:

$$\mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})}. \tag{2}$$

Inverting these expressions directly yields the ratio of the free neutron to proton structure functions:

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}} \ . \tag{3}$$

We stress that F_2^n/F_2^p extracted via Eq.(3) does not depend on the size of the EMC effect in ^{3}He or ^{3}H, but rather on the *ratio* of the EMC effects in ^{3}He and ^{3}H. If the neutron and proton distributions in the $A = 3$ nuclei are not dramatically different, one might expect the super-ratio, $\mathcal{R}$ to be approximately one. To test whether this is indeed the case requires an explicit calculation of the EMC effect in the $A = 3$ system. The super-ratio

$\mathcal{R}$, calculated by Afnan et al. [5], is shown in Fig. 2 for the various nuclear model wave functions (PEST, RSC and Yamaguchi), using the CTEQ parameterization [6] of parton distributions at $Q^2 = 10$ GeV^2. The EMC effects are seen to largely cancel over a large range of x, out to $x \sim 0.85 - 0.9$, with the deviation from the central value, $\mathcal{R} \approx 1.01$, lying within $\pm 1\%$. Furthermore, the dependence on the nuclear wave function is very weak.

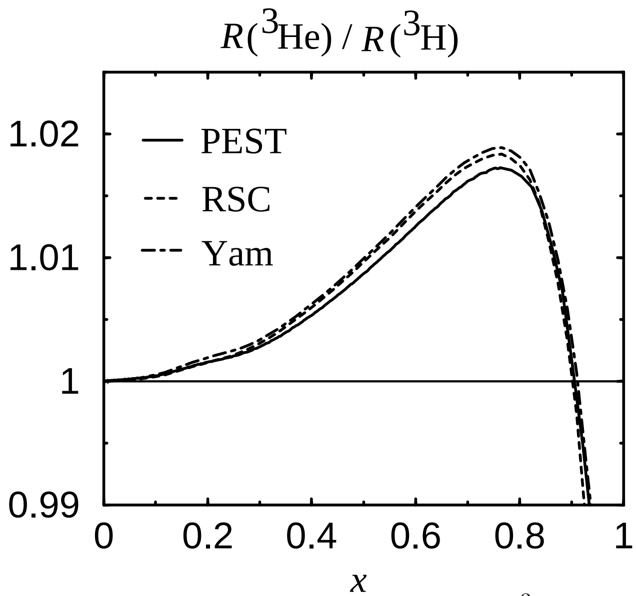

FIG. 2. Super-ratio of the nuclear EMC ratios for ^{3}He and ^{3}H for various nuclear models: PEST (solid), Reid Soft Core (dashed), Yamaguchi (dot-dashed) – from Ref. [5].

In addition to the dependence on the two-body force used one also needs to test the sensitivity of $\mathcal{R}$ to the assumed nucleon structure functions. The detailed study may be found in Ref. [5]. For our purposes it is enough to say that while there is some sensitivity one can adopt a straightforward iterative procedure which is quite rapidly convergent, so that starting from standard distributions, like CTEQ, one can quickly converge to a self-consistent set of structure functions and $\mathcal{R}$. The corollary to this is that having determined $F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}$ and $\mathcal{R}$, one will not only pin down F_2^n/F_2^p but will also determine the EMC effect in ^{3}He and ^{3}H, as well as the deuteron, thus completing our experimental knowledge of the nuclear EMC effect [7]. This will be a vital assistance in sorting out the origin of this famous effect [8], especially the possible change of nucleon structure in a nuclear medium, which is fundamental to our understanding of QCD itself.

III. SPIN DEPENDENT VALENCE DISTRIBUTIONS

As noted earlier, the case for the determination of the spin dependent structure functions in the region $x > 0.5$ is even clearer – there is no data in this region at all! One does not even know, for example, whether the neutron spin structure function, g_{1n}, becomes positive in this region! This was highlighted, for example, in the presentation of Leader who made important connections to "old fashioned" analysing power data ($A^{\uparrow} + B \to C + X$) [12]. It is remarkable that the focus on the "spin crisis" has diverted so much effort to small x that nothing is known in the large x region. While there is room for more work, especially on exchange current corrections (mesons, Δ's, etc.), it seems that one can determine g_{1n} relatively well from measurements with a polarized ^{3}He target [9], while accurate data on the proton may be simplified by the development of a better $\vec{p}$ target.

It is clear that Jefferson Lab, with the 12 GeV upgrade, can provide a definitive picture of the spin dependent valence structure functions in the large x region, thus completing one of the fundamental tasks of the international program in deep inelastic scattering. On the theoretical side, apart from the comparison with QCD inspired models [10], one can expect these distributions to be accessible to lattice QCD over the same time frame [11].

IV. TWIST-3 STRUCTURE FUNCTIONS

A compelling case was presented by Ji, Bosted, Averett, Meziani and others that following the proposed upgrade, Jefferson Lab could determine g_2 for both the proton and neutron, with an order of magnitude improvement in statistical accuracy in the range $x \in (0.3, 0.8)$. This would enable one to remove the trivial twist-2 contribution and unambiguously isolate the twist-3 piece. As this involves *totally novel* information on the internal structure of the target, it should provide extremely important new information on the internal structure of hadrons [13]. For example, the second moment of the twist-3 part of g_2, d_2, involves the matrix elements $\langle ps|\psi^\dagger \vec{B} \psi|ps\rangle$ and $\langle ps|\psi^\dagger \vec{\alpha} \times \vec{B} \psi|ps\rangle$, where $\vec{B}$ is the color magnetic field inside the hadron. This will be the first indication of the correlation of the quark and gluon fields inside a hadron.

V. CONCLUSION

The consensus of the participants at this workshop were that, following an upgrade to 12 GeV, Jefferson Lab would be able to provide important and definitive answers to our questions concerning the spin and flavor distributions of the valence quarks in the nucleon. It would also be able to provide the first unambiguous information on the twist-3 structure functions of the nucleon, that is the correlations between quarks and gluons in the proton. This represents an outstanding physics program.

As a side benefit of the determination of the valence d distribution we would also have accurate measurements of the EMC effect in ^{3}He, ^{3}H and the deuteron for the first time, thus allowing a complete study of the nuclear EMC effect and the possible change of nucleon structure in medium.

Following these top priority investigations there are numerous other important studies to be made. It is vital to explore the validity of Bloom Gilman scaling [14] for spin structure functions [15]. As we have already seen from Jefferson Lab data, scaling may well work where one has no theoretical reason to justify it (yet). If it can be shown to work one could use the technique to study a host of quantities at large x, notably $\bar{d}-\bar{u}$, $s-\bar{s}$, Δs, etc. As explained in detail by Mulders, Leader and Ent [16], semi-inclusive measurements allow us probe a large number of new observables. As emphasised by Mitchell, one can also use a tensor polarized target to determine the new spin structure function b_1, which is expected to be significant at large x. One could investigate the spin dependence of the EMC effect at large x [17] using $^3\vec{\mathrm{He}}$ and $\vec{\mathrm{D}}$ targets. As emphasised by Brodsky and Liuti, one can investigate quark and gluon correlations in the nucleon by measuring higher twist structure functions. As discussed by Kumar, parity violation can also be exploited to study parton distributions.

In summary, there is an urgent physics case for the 12 GeV upgrade in order to answer vital and topical questions which go to the heart of our understanding of strongly interacting systems.

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[1] W. Melnitchouk and A. W. Thomas, Phys. Lett. **B377**, 11 (1996) [nucl-th/9602038].

[2] G. R. Farrar and D. R. Jackson, Phys. Rev. Lett. **35**, 1416 (1975); S. J. Brodsky, M. Burkardt and I. Schmidt, Nucl. Phys. **B441**, 197 (1995) [hep-ph/9401328].

[3] U. K. Yang and A. Bodek, Phys. Rev. Lett. **82**, 2467 (1999) [hep-ph/9809480].

[4] M. Botje, Eur. Phys. J. **C14**, 285 (2000) [hep-ph/9912439].

[5] I. R. Afnan, F. Bissey, J. Gomez, A. T. Katramatou, W. Melnitchouk, G. G. Petratos and A. W. Thomas, nucl-th/0006003.

[6] H. L. Lai *et al.* [CTEQ Collaboration], Eur. Phys. J. **C12**, 375 (2000) [hep-ph/9903282].

[7] J. J. Aubert *et al.* [European Muon Collaboration], Phys. Lett. **B123**, 275 (1983); D. F. Geesaman, K. Saito and A. W. Thomas, Ann. Rev. Nucl. Part. Sci. **45**, 337 (1995); M. Arneodo, Phys. Rept. **240**, 301 (1994).

[8] W. Melnitchouk, I. R. Afnan, F. Bissey and A. W. Thomas, Phys. Rev. Lett. **84**, 5455 (2000) [hep-ex/9912001].

[9] C. Ciofi degli Atti and S. Liuti, Phys. Rev. **C41**, 1100 (1990).

[10] A. W. Schreiber, P. J. Mulders, A. I. Signal and A. W. Thomas, Phys. Rev. **D45**, 3069 (1992).

[11] C. Best *et al.*, hep-ph/9706502.

[12] M. Boglione and E. Leader, hep-ph/0005092.

[13] X. Ji and J. Osborne, Eur. Phys. J. **C9**, 487 (1999) [hep-ph/9902393].

[14] E.D. Bloom and F. J. Gilman, Phys. Rev. Lett. **16**, 1140 (1970).

[15] W. Melnitchouk, hep-ph/9909463.

[16] A. Bacchetta and P. J. Mulders, hep-ph/0006131.

[17] F. M. Steffens, K. Tsushima, A. W. Thomas and K. Saito, Phys. Lett. **B447**, 233 (1999) [nucl-th/9810018].